From Z-Machines to ALMA: (Sub)millimeter Spectroscopy of Galaxies
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Tracing the Evolution of Disk Galaxies with Galactic Structures and Gas Kinematics

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Abstract. Current evidence suggests that the epoch of disk formation occurred between $1 < z < 3$. What were the properties of galaxy disks at the epoch of their formation? How did they evolve to their present state, and how was the Hubble sequence assembled? Although large and comprehensive datasets such as COSMOS, GEMS, and GOODS are now becoming available, it is possible that these questions will remain unanswered because of the difficulty in obtaining redshifts from optical spectroscopy as emission lines are redshifted into the infrared. This historical shortcoming has also hampered millimeter and submillimeter studies where the limited bandwidth and sensitivity of current telescopes have restricted studies to only a handful of bright galaxies with spectroscopic redshifts. With the future generation of z-machines, we can overcome the current obstacles and combine optical, infrared, millimeter, and submillimeter observations to trace the evolution of disk galaxies. In this contribution, we describe a research strategy to study the assembly of disk galaxies using space- and ground-based telescopes at multiple wavelengths. In particular, we emphasize the critical role of z-machines and millimeter/submillimeter interferometers.

1. A "Typical" Submillimeter Galaxy at $z \sim 2$: SMM J16359+6612

In the past decade, submillimeter observations with single-dish telescopes have identified hundreds of galaxies. Most of these are relatively bright with fluxes $S_{850\,\mu\mathrm{m}} > 5\,\mathrm{mJy}$. This population is believed to be the progenitor population for today's massive ellipticals. Although numerous, these bright submm galaxies do not constitute the bulk of the submm background, which is dominated by sources with $S_{850\,\mu\mathrm{m}} < 1\,\mathrm{mJy}$. These sources cannot be studied easily with existing instrumentation because they are below the confusion and sensitivity limits. One way to probe the "garden-variety" submm galaxies is via a foreground gravitational lens that amplifies the signal and magnifies the image. However, the chances of finding a faint submm galaxy near the caustic of a lens that will allow for a large magnification are small.

One fortuitous case is SMM J16359+6612 ($S_{850\,\mu\mathrm{m}} = 0.8\,\mathrm{mJy}$), which lies near the caustic of the well-studied cluster Abell 2218. First identified by Kneib et al. (2004), SMM J16359+6612 is magnified by a factor of 45. The redshift derived from an Hα line measurement is $z = 2.515$. The galaxy is part of a group of four galaxies all within 130 kpc of each other. We mapped the CO($J = 3-2$) line emission from SMM J16359+6612 using the Owens Valley Radio Observatory in 2003 October. In just 20 hours of integration, we were able to detect all three images of the galaxy, as shown in Figure 1. This observation is the current record holder for detection of molecular gas in the faintest submm galaxy. It allows us to explore the properties of a "typical" submm galaxy at the epoch of galaxy formation.

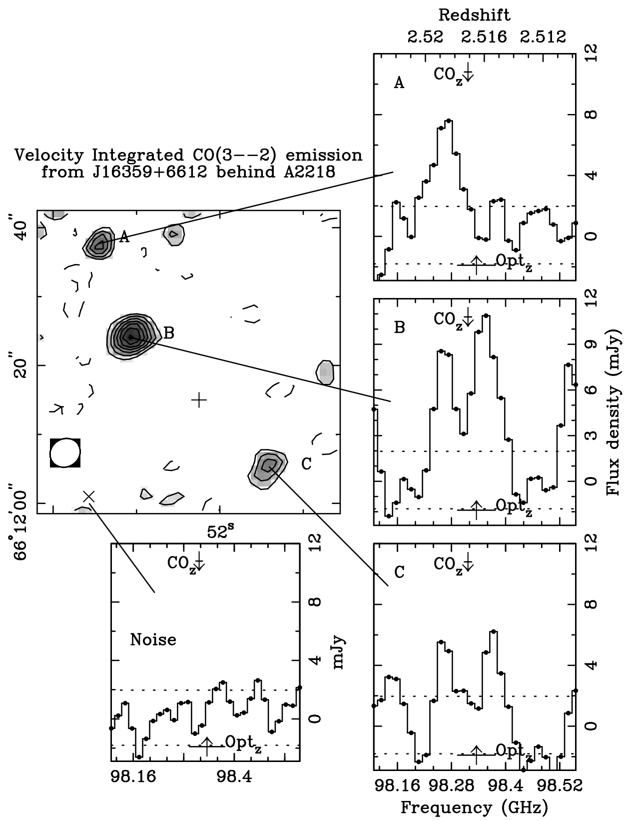

Figure 1. CO($J = 3 - 2$) emission from SMM J16359+6612 from OVRO observations. The three panels on the right show the spectra from each of the images of the lensed galaxy. The double-peaked velocity profile is the most striking feature of these spectra. Details about the observation and analysis are presented in Sheth et al. (2004).

The total molecular gas mass in SMM J16359+6612 is $(0.5 - 2) \times 10^{10}\,M_\odot$– similar to the molecular gas mass in the Milky Way. Given the estimates of the star formation rate (from Hα and dust continuum measurements), the gas consumption timescale is very short, 50–100 Myr. The double-peaked profile in the spectra is reminiscent of a disk or ring morphology. This spectral signature combined with the molecular content and star formation activity suggests that SMM J1639+6612 may be a scaled-up version of local starburst nuclei. The dynamical mass is $10^{11}\,M_\odot$; this is an order of magnitude higher than Lyman break galaxies, but at the low end of dynamical masses measured for the bright submm galaxies. The gas mass fraction is low (1–25%). From these data, we therefore conclude that SMM J16359+6612 is unlikely to evolve into a massive elliptical galaxy. Instead, it appears to be a modest galaxy with properties that are between those found for lower-mass Lyman break galaxies and the higher-mass submm galaxies. The galaxy appears to be undergoing a starburst phase that may be induced by on-going interactions with its neighbors. It is possible that the bulk of the submm background is contributed by galaxies like SMM J16359+6612 that are modest-mass galaxies undergoing active star formation but unlikely to develop into massive ellipticals without significant additional merging.

2. Galaxies at $z < 2$: Measuring the Assembly of Disks

While objects like SMM J16359+6612 may represent our best chance for studying the "typical" galaxy at $z > 2$, the assembly of the Hubble sequence has likely occurred over the last 10 Gyr ($z < 2$). With existing and upcoming instrumentation, we can exploit this action-filled epoch of galaxy evolution. It is in this epoch that z-machines will make important contributions. Below we describe our strategy for studying the assembly history of disk galaxies.

In the last five years, we have seen a plethora of large surveys (e.g., COSMOS, GOODS, GEMS, SWIRE). Of these, the most ambitious and comprehensive is the two square degree COSMOS survey[1] (Scoville et al. 2007). Initially an ACS survey, this study has data from X-rays to the radio, including IRAC and MIPS data from *Spitzer*. There are key advantages in studying the galaxies in the COSMOS field. The field contains over two million objects at $I_{\rm AB} < 27$, with over 16,000 L^* or brighter galaxies at $z < 1$. We are conducting an extensive optical spectroscopic survey of the bright galaxies in the field, which will yield 25,000 galaxies at $0.3 < z < 1$ and 12,500 galaxies at $1.4 < z < 2.5$. The field is large enough and deep enough to allow an exploration of galaxy morphology as a function of both redshift and large-scale structure. It is also an equatorial field, accessible from most telescopes in the northern and southern hemispheres (e.g., VLT and Keck, CARMA, SMA, APEX, and ALMA).

With the COSMOS field as a finding chart, we are (and will be) measuring the evolution of mass of all the structural components in galaxies. Already smaller surveys like GOODS, DEEP2, and GEMS are using optical and IR data to measure the evolution of the stellar mass. But these studies are only partially complete without measurements of the gas, dust, and dynamical masses. Using future z-machines, we will measure the gas and dust mass, and dynamical masses using CARMA, IRAM, SMA, OSIRIS, and ultimately ALMA.

As shown in Figure 2, the parameter space at $z < 2$ is largely unexplored. In this figure, we show calculations of the feasibility of CARMA observations for gas-rich galaxies as a function of redshift. CARMA will have a broadband spectrometer; however, it is unlikely to be broad enough to search for galaxies with photometric redshifts alone. Therefore, the COSMOS data with their large number of spectroscopic redshifts are ideal for follow-up with millimeter interferometers like CARMA.

3. Conclusions and Future Prospects

In the near term, we have to rely on optical or near-infrared spectrometers for precise redshifts for follow-up studies of molecular gas. In the future, we will be able to forego this dependence with z-machines. Z-machines like Z-Spec, the Redshift Search Receiver (LMT), the Zpectrometer (GBT), ZEUS (CSO,

[1] `http://cosmos.astro.caltech.edu/`

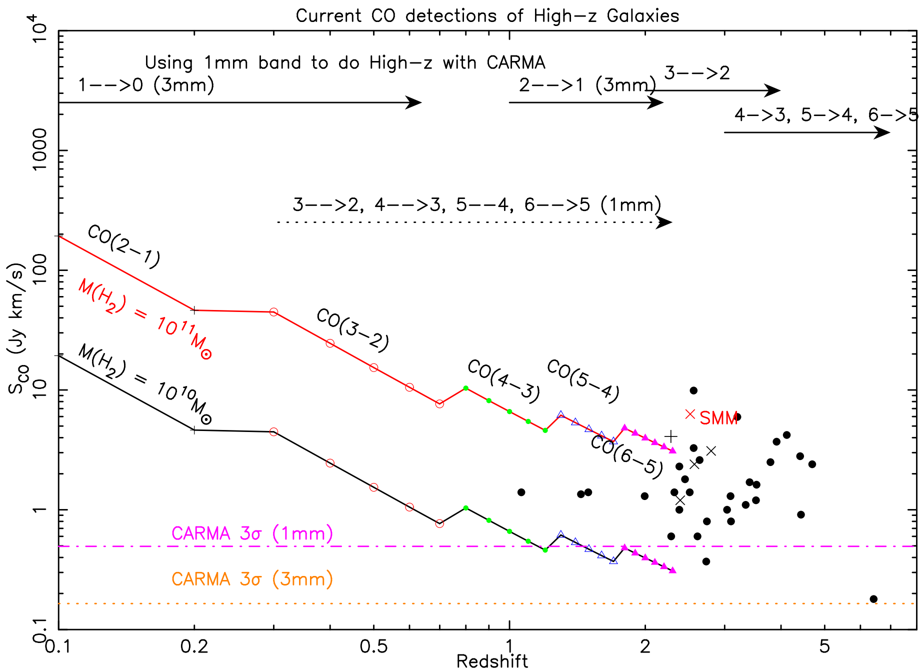

Figure 2. Calculations of the expected signal to noise for galaxies with 10^{10} and 10^{11} $M_\odot$ of H_2 using different emission lines of CO to detect the galaxy in the 3 mm band. The line fluxes are estimated from Solomon, Downes, & Radford (1992). The current observations of molecular gas in high-z objects are shown, along with SMM J16359+6612, which was discussed earlier. Notice the paucity of sources studied at $z < 2$. With two tracks of integration, CARMA should be able to observe gas-rich galaxies easily to $z \sim 1$; a similar calculation for 1 mm shows that one can extend the horizon of observations of gas-rich disks to $z \sim 2 - 3$.

APEX), and COBRA (CARMA) will be ideal instruments for surveying large fields. With these we will determine redshifts and measure the cosmological evolution of the total molecular gas and dust masses in disks. Molecular gas-rich galaxies can then be observed with interferometers like CARMA, IRAM, and ALMA, and optical/NIR IFUs such as OSIRIS, PIFS, SINFONI, etc. These data will be critical for measuring the enclosed dynamical mass and inferring the dynamical state of the galaxy disks. In principle, one can use the kinematics to infer the presence of galactic structures like bars and spiral arms. Thus, z-machines with large multi-wavelength fields like COSMOS can trace the mass evolution of disks and the assembly of the Hubble sequence.

References

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